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PROBLEMS OF ATOMIC REACTOR-LASERS

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16. Abstract

The preliminary directions to be pursued in correcting and implementing basic atomic reactor-laser concepts are outlined. The basic measures to be followed in implementing such systems are discussed.

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PROBLEMS OF ATOMIC REACTOR-LASERS

The Idea of an Atomic Reactor-Laser [1]

It is not our thought to prove the assertion that the atomic reactor is the basis of the most promising of the current ways of obtaining energy. With the exhaustion of natural resources of traditional fuel, atomic electric power stations are rapidly acquiring decisive importance in the energy technology of many countries. These devices, which make use of the newest apparatus, optimal materials, and the foremost technical solution of various problems, are unquestionably related to the most important achievements of engineering-physics. However paradoxical it may sound to the majority of physicists not directly connected with the development of reactors, we must begin an account of this work with the assertion, that, in essence, an archaic, principally backward method of obtaining electrical energy is being used in all atomic electric power stations. This is not only the personal point of view of the authors of this work; the most prominent atomic physicists never cease regretting this. Such an attitude toward atomic reactors is not news; it arose in developing the first installations and was even reflected in the very names given; evidently, by E. Fermi: "atomic furnace," "atomic boiler". The "steam engine" feeling of the names, which is slightly vexing in regard to a wonderful, modern installation, is connected with the fact that in atomic reactors, the energy of fission, liberated in the initial moments, is not transformed directly into electrical energy, but is first transformed into heat. But it was S. Carnot who is credited with recognizing the fact that the thermal form of energy is the poorest in quality. Heat can only partially be transformed into electricity, in accordance with the comparitively low efficiency of the thermal machine. Thus, even in the best atomic electric power stations, the efficiency (of the change of the nuclear fission energy liberated in the reactors into electricity) is only approximately one-third. The theme of this work is the discussion of a means of deriving energy from atomic reactors which allows us to radically improve their characteristics. From the following it will be evident

that the basis of the new means set forth here is closely connected with the recent progress of physics in several "non-nuclear" directions. Thus the duration of nonconstructive regrets about the thermal means of using nuclear energy is not so surprising.

To avoid the thermal methods, one must not assume the thermalization of the nuclear-active medium, or, in other words, must not assume "equal partition" in terms of degree, freedom of the high-quality kinetic energy of nuclear "fragments". To this end, it is necessary to know how to withdraw energy from an atomic reactor while still in an essentially nonequilibrium phase, i.e., in a time less than the relaxation time of the medium. Naturally, for the successful implementation of such a problem one must, on the one hand, "slow down" as much as possible the processes which lead to the establishment of thermal equilibrium in the reactor, and on the other hand, turn to methods of the most rapid withdrawal of energy from a body. By comparison with usual high-energy atomic reactors, the time of relaxation can be increased by several orders of magnitude. To this end, it is necessary to transfer from traditional reactors using solid "fuel" (uranium, plutonium) to so-called gas-phase reactors, in which the chemical compound of uranium (plutonium), found in the gas phase under operating conditions, serves as the material undergoing fission. The most rapid practical method for the withdrawal from a nuclear reactor of the energy of nuclear fission must begin, evidently, with its transformation into electromagnetic radiation. This radiation must have a structure which allows it to be extracted from the reactor without great losses. It is natural in this case to study the possibilities of transforming the basic portion of the energy of the fragments into the characteristic radiation of atoms and molecules. In this problem, it is of course not necessary to calculate the spontaneous radiation of the medium filling the reactor, which goes out in directions in wide bands of frequencies and is in fact absorbed by the medium. We are talking here only about the use of forced (induced) transitions under conditions in which the medium effectively amplifies the corresponding radiation. The amplification of the light presumes the existence of an inverse population of the energy levels of the medium in the course of the deviation from thermodynamic equilibrium created by fragments of nuclear fission.

Thus we arrive at the conclusion that it is wise to analyze the possibilities of transforming the energy of fragments of an atomic gas-phase reactor into laser radiation. Twenty or thirty years ago, a problem stated in such a way would have seemed strange at best to the overwhelming majority of physicists. Even now it may seem premature to a number of specialists. This caution is easily understood, since a great variety of questions immediately arises.

First of all, it is natural to question the practicality in general of gas-phase reactors. After all, could it happen, with the boiler filled with a gas-phase compound of U (or Pu), that the critical mass could turn out to be unattainable from the supplementary (by comparison with the pure material undergoing fission) loss of neutrons which always arise in such compounds. Perhaps such installations will always be extremely inconvenient practically. For example, they might have to have great weight and dimensions, be extremely expensive, hard to run, etc. All of these questions, of course, must be answered in detail. But such a discussion will take a great deal of time and - as we are trying to explain - it relates more to the stage of choosing and calculating optimal constructions. So as not to answer each such question in detail, we will essentially say only that the experimental gas-phase reactors using hexaflouride of uranium of generally acceptable parameters do exist. The weight of this gas at a high degree of enrichment is rather small; for obtaining critical mass with a $\sim$90% fraction of U^{235}, 20-30 kg of gas is sufficient. The pressure of such a gas may not exceed the atmosphere, and the internal linear dimensions of the boiler of such a reactor can be small; on the order of 1 m. The filler of such reactors is uranium flouride, UF_6. This is a gas-phase compound, rather common in reactor technology, since it is used as an intermediate product in the separation of isotopes of uranium. We will not enumerate at this time the great number of advantages of gas-phase atomic reactors over traditional reactors. It is more essential in this case to note that, for such energy installations, specific inconveniences would be characteristic. Not the least important of these would be the necessity of reconstructing the units making the operation of the reactors reliable.

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The fact is that the material undergoing fission in the case that is of interest to us is a gas which is not only radioactive, but also very poisonous. Gas-phase reactors are not yet on a par with other atomic electric power stations, in a large measure because of this inconvenience.- particularly because until recently, perhaps, there has not been a single-clear-cut stimulus for the expenditure of equipment and time for developing and introducing such devices.

No less important for us is the set of questions connected with the process of the transition of nuclear fission energy into laser radiation. The possibilities for such an effective transformation of energy are determined by several initial considerations.

1. A basic fraction of the energy of nuclear fission is concentrated in the kinetic energy of fragments which are multiply-charged ions (chemical elements with atomic weights approximately one-half of those of U, Pu).

2. By far the largest part of the energy of fast, repeatedly-ionized particles is used up in ionization as they move in the medium.

3. The ionization of a cold, dense gas by fast, charged particles, after a rather short time leads to a recombined type of nonequilibrium of the plasma produced. This type of nonequilibrium is characterized by high density of free electrons, recombined relaxation of charged particles and very high populations of excited electron states of atoms (molecules and ions), which can exceed their equilibrium values by ten or more orders of magnitude.

4. Recombined dense plasma with the appropriate composition, effectively strengthens the characteristic radiation of its atoms (molecules, ions). A series of important advantages of such a active medium over more traditional media allows us to expect high energy parameters of the "plasma layers" using it [2].

For the transformation of the kinetic energy of fragments into induced radiation, we need a sufficient equilibrium of the plasma corresponding to the rate of recombination, and then to have the frequency of nuclear fission exceed some threshold value $G > G_{\text{пор}}$. On the other hand, since in any case an appreciable part of the energy of fission will change into heat anyway, and if the temperature $T > T_{\text{кр}}$ of the gas is too high, the inversion of

the population of atomic (molecular, ionic) levels will cease, we must consider another limit value of the frequency of nuclear fission, which, if exceeded, will cut off the amplification of the light from the overheating of the gas ($T > T_{кр}$ with $G > G_{кр}$). Consequently, the reactor must be constructed so that the boundary frequencies of fission, determined by its parameters, per unit volume of the gas-phase medium will satisfy with a margin of safety the condition

$$G_{кр} > G_{пор}. \qquad (1)$$

The basic features of the types of atomic reactors discussed here, in addition to the gas-phase of the fuel with which they are filled, are determined also by the extent of one of the linear dimensions. Effective laser extraction of energy is possible only with a long reactor so that light is amplified sufficiently in the laser-active medium. In regard to the devices under discussion, we must also specifically take into account certain properties which are usually considered in the construction of reactors. First of all, it is essential that the mean free paths of neutrons in the medium be comparatively large, while at the same time, the mean free paths of the fragments should be rather short. In a gas with a density appropriate for this problem ($N \sim 3 \cdot 10^{20} \div 10^{21}$ [illegible]), the mean free paths of fast fragments (ions ionized approximately 20 times) turn out to be $l_{т.р} \lesssim 10^{-1}$ см . In the conditions analyzed below, we need not take into account the diffusion of solid charged particles of a sufficiently cold, dense plasma, because the medium recombination zone practically coincides with the zone of its ionization by fragments. Therefore the radiation is amplified only in those domains in which nuclear fission is taking place, i.e., the nuclear- and laser-active zones must coincide. Thus, in discussing the possibilities for the effective laser extraction of energy from an atomic reactor, we should not discuss which form of the laser is located within the atomic reactor [3], but rather to a single energy installation, reactor-lasers (RL).

We must now discuss a whole series of modifications of RL's and their respective classifications by various indices, some of which have a primarily nuclear basis, while others have a mainly optical basis. Due to the nature of the operation of an atomic reactor, we must first of all distinguish between stationary and

thermal-impulse RL's. In reactors of the first type, the necessary operating conditions ($T < T_{кр}$) are ensured by the continuous heat transfer from the active zone. The second type of reactor uses, first of all, the heat capacity of the system itself. But even here (in the case of energy applications, as far as possible, of light impulses which are often repeated) it is not possible to avoid the forced extraction of heat from the active zone. Therefore the construction of all such systems must make provision for the partition of the installation into a rather large number of energy-discharging elements (EDEL's) washed by a coolant, with at least one comparitively small linear dimension, perpendicular to the direction along which light is amplified in the active medium. A common neutron field connecting the whole RL into a single installation is supplied by (and is used by) the gas-phase fuel of each of these elements. The transverse dimensions of the EDEL must not be too small, or the energy of the fragments which is lost in the walls will lower the efficiency and, besides, the loss of neutrons will grow.

Based on light characteristics, pulsed RL's can be in principle optically quasi-stationary and optically pulsed. Furthermore, we must distinguish between RL's (both steady-state and pulsed) in terms of light autonomy. The first class includes generators with a laser feedback formed by mirrors (in such RL's, the unsaturated amplification of the light as it passes along the active medium must exceed the losses in the resonator.) To the second class belong light amplifiers, which allow us, in general, to avoid vulnerable (liable to be damaged by radiation from the fragments and the corrosive medium) mirrors, but which require in return the supply at the input a powerful light emission of the appropriate frequency from the external generator. A compromise variant is also possible; the generation, without mirrors, of "super-luminescence" under operating conditions. In an analogous "nuclear" classification, it is interesting to examine properties at RL which are critical relative to neutrons and their subcritical types (booster and hybrid).

We now move on to a more epecific exposition of several of the projected general questions.

EQUILIBRIUM OF THE ACTIVE MEDIUM OF RL'S

First we will discuss the deviation of the gas-phase medium which fills the energy-discharging elements* (EDEL's) from thermodynamic equilibrium. First of all, this medium rarely becomes nonequilibrium in terms of the velocity distribution of heavy particles in the acts of fission of uranium atoms, since the fission energy is converted mainly into the kinetic energy of multiply-charged ions, or "nuclear fragments". As a rule, a pair of fragments with energy $\sim$ 100 MeV each are separated immediately after fission. These particles fly into the comparitively cold gas which fills the EDEL. The overwhelming mass of molecules of this gas has a small energy corresponding to the temperature T $\sim$ 0.3 eV. Thus, the particles, whose mean density $\rho_{\text{ост}} \simeq M_U G \tau_{\text{ост}}$ (M_U is the mass of a uranium atom, $\tau_{\text{ост}}$ is the characteristic time of the wasting of energy by the fragments) is very small, each have energy $\sim 10^9$ times greater than the mean energy of one molecule in the gas. The space and time combination of two such groups naturally characterizes an extremely nonequilibrium situation with low entropy. Such a situation allows us to turn the major part of the energy liberated by fission into work.

The next stage of energy conversions in the dense, cold gas which fills the EDEL is determined by the ionization of this gas by fragments. In the course of this external ionization, plasma is formed of a low (in absolute quantity) degree of ionization $\alpha \equiv N_e/N$ (N_e is the concentration of free electrons, N is the density of the gas). But this quantity α turns out to be higher than the thermodynamic equilibrium value of the degree of ionization corresponding to the given density of the gas and the temperature T_e of the free electrons which was obtained under these conditions. Thus (we emphasize this again) EDEL are filled with overionized plasma. It is clear that the same thing can be said in another way; in this plasma, with the free electron density obtained in the course of the processes which accom-

*This is different from the usual terminology of atomic reactors. The traditional term "heat-releasing element" (HDEL) does not reflect the nature of energy of an RL

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pany nuclear fission, the mean energy (temperature) is low. The concepts of "overionization" of plasma and "supercooling" of its free electrons are equivalent. They characterize the recombination type of its nonequilibrium; in such a homogeneous plasma, the relaxation to equilibrium is determined, obviously, by the volume recombination of free electrons with ions.

As we have already noted, the immediate reaction of fast multiply-charged ions with the medium of EDEL reduces almost totally to the ionization of molecules. The elastic collisions of these ions which heat the gas, as well as the nonelastic collisions, which excite the molecules at discrete levels have much smaller probabilities than the ionizing collisions. But the effective relaxation reactions of the free electrons which are formed in this way with the cold, dense gas *does not allow the fast ions to swing the collective plasma* oscillations. This reaction leads to the fact that nonequilibrium of the electron distribution in the continuous spectrum forms the essential difference from the Boltzmann law in the population of a series of connected quantum states of the gas molecules. Part of the discrete energy levels turn out to be overpopulated and another part turn out to be underpopulated. Precisely as a consequence of this, the characteristic emission of molecules can be used in the gas filling the EDEL for the extraction of energy from a reactor-laser; the emission can be amplified simultaneously not from one, but from a series of various transitions (electron, vibrational, vibrational-rotational). But here, for definiteness, we will have in mind primarily the amplification at transitions of molecules (atoms) between electron terms. The relaxation of super-cooled plasma forms a recombination flow of electrons along the energy levels from the continuous spectrum of molecules to their basic state. This leads to overpopulation of the high-lying states, which are more closely connected to the continuum, and to the underpopulation of the low-lying states which are adjacent to the basic state. Under judiciously selected conditions at the transitions, there arises an inversion of populations precisely between such groups of levels. This inversion can be used for strengthening of the radiation.

The recombination flow, which is determined by the ionization of the gas by nuclear fragments, is obviously a pumping of the "laser component" of the atomic reactor. This pumping can be either pulsed

or stationary. In the pulsed variant, it is possible in principle that the burst of the number of fissions can be so sudden that the non-equilibrium of the distribution of free electrons, now of the ionization type, may correspond to the increased concentration of free electrons induced by the burst. The inversion of the population of the discrete levels can also be connected with this type of deviation (N_e, T_e) from equilibrium. It is precisely this type of non-equilibrium (few superheated electrons, the process of ionization occurs) that characterizes the active medium of a different kind of "gas laser" (whose active medium is recombining plasma). But it is important to bear in mind that "gas laser" schemes of light amplification are not appropriate under RL conditions. It has already been noted that, to achieve the critical mass of uranium for all EDEL with judicious reactor dimensions, the gas which fills it must be sufficiently dense. With the increase in density, it becomes more and more difficult to create the superheating of free electrons at a low gas temperature necessary for the formation of the ionization type of nonequilibrium: the pulse of fissions must be made shorter while the gas superheats more rapidly. The "gas-laser" method loses practically all effectiveness at some concentration of gas near $N \sim 10^{18}$ cm^{-3}. For the productive operation of RL, a density of at least 2-3 orders of magnitude higher is needed. After the fission pulse has passed, a state of recombining relaxation begins during which the realization of nonequilibrium by the amplification of light and the extraction of energy in this way can be made sufficiently effective. But under the conditions which we have discussed here, the relaxation of populations of molecules and atoms occurs rather quickly in the time $\tau \lesssim 10^{-8} \div 10^{-7}$ sec. Thus, even under conditions of a very short, technically real fission pulse, the amplification of light must still arise before the end of this pulse. Consequently, in the analysis of a RL we must first discuss the quasi-stationary (or stationary) modes.

We begin with the previous assertion that under quasistationary working conditions in the gas which fills the EDEL nonequilibrium of the recombination type is always established. We will establish this, limiting ourselves to the three-dimensional homogeneous stationary conditions. Let z denote the mean number of electrons generated in the gas by the whole "cascade" of ionizations produced by one act of

fission of a uranium nucleus. To estimate this number, we write $z \simeq \frac{E_{\text{дел}}}{E_{\text{пар}}} \simeq \frac{2 \cdot 10^8\ эв}{20\ эв} = 10^7$. Here $E_{\text{дел}} \simeq 200$ MeV is the initial kinetic energy of the separated fragments and $E_{\text{пар}} \simeq 10 \div 30$ eV is the energy consumed (in the cascade of ionizations accompanying fission) for one ionization (the apperance in the plasma of one new pair, a molecular ion and an electron). The rate of change of the density of free electrons is determined by the acts of fission of nuclei, volume recombination of charged particles, and the ionization of the gas by eigen electrons. Supposing the degree of ionization of the medium is very small ($\alpha \leq 10^{-5}$), we will assume for simplicity that the basic act of recombination is a triple collision with the participation of a neutral molecule. Assuming in addition that, because of the small degree of ionization, the densities of electrons and ions are equal, we have

$$dN_e/dt = zG - K_e N_e^3 + SN_eN. \tag{2}$$

The changes in time of the temperature T_e of the free electrons are determined by the energy intensity W of the reactor laser and the effectiveness of the selection of the electron energy by the gas:

$$\frac{3}{2}\frac{d(N_eT_e)}{dt} = W - \langle \sigma v_e \rangle |N_eN, \tag{3}$$

where $W = GE_{\text{дел}}$ is the power released during fission per unit volume of the medium, $\sigma = \sigma' = \sigma''$ is the effective cross section of the exchange of energy between electrons and molecules, $\sigma' = \frac{2m}{M}\sigma_{\text{упр}}(T_e - T)$ is the cross section of the elastic transfer of energy, m and M are the masses of an electron and a molecule, $\sigma_{\text{упр}}$ is the cross section of the pulse exchange, $v_e = \sqrt{\frac{3T_e}{m}}$ is the thermal rate of an electron and σ'' is the total characteristic of the probabilities of electron and vibrational-rotational transitions of molecules during collisions with free electrons. In a dense gas with a large concentration of molecules, $\sigma'' > \sigma'$ as a rule. The superheating of the gas to a temperature higher than the critical temperature $T_{\text{кр}}$ (dependent on the gas composition and the choice of "working" levels* and usually lying at the limit $T_{\text{кр}} \sim 1 \div 2$ eV), disrupts conditions for the effective amplification of the light. Assuming that the condition $T_e \ll T_{\text{кр}}$ holds, we can, as a rule, disregard the equilibrium radiation of the gas in a

*In quantum electronics, it is accepted to refer in this way to the energy levels of the active medium, between which the induced transitions determine the strengthening of the radiation by the medium.

first approximation. But the reaction of the molecules with supercooled (precisely as a consequence of this) free electrons leads to great nonequilibrium of the populations of the excited states. As a result of this reaction, there arises, in particular, an inversion of the population of molecules at the working transitions. Taking this into account, the equation which estimates the rate of change of the gas temperature T (more precisely, the temperature of the heavy particles) can be presented in the form

$$\frac{3}{2} N \frac{dT}{dt} = [\langle \sigma' v_e \rangle + (1 - r) \langle \sigma'' v_e \rangle] N_e N - Q, \qquad (4)$$

where the dimensionless parameter r effectively describes the fraction of the energy of excitation of the molecules by electron collisions which leaves the gas with the radiation. Here Q is the mean rate of heat transfer from the gas to the walls of the EDEL. For a more detailed description of the relaxation of the active medium, we must take into account the level-by-level kinetics of the population; then in place of the effective parameters σ" and r, we enter a larger group of quantities (namely, parameters and variables), into equations (2) - (4). We will not stop and discuss at this time such a description, which must be gone through anew for each specific variation of the chemical composition of the active medium. Neither will we take into account at this time the nonhomogeneous conditions along the transverse cross section and along the length of the EDEL.

In equations (2) - (4) we can frequently set $dN_e/dt = 0$, $dT_e/dt = 0$ assuming the dependence of T_e and N_e on the time t can be linked only with changes of the gas temperature T(t). Such a "quasi-stationary consideration" is justified for a nonconstant gas temperature. This is true because, with low degrees of ionization, when $\alpha \ll T/E_{\text{пар}}$ (here we are only thinking of examining such a plasma) the characteristic time τ_T of the change of gas temperature exceeds the relaxation times τ_{N_e} and τ_{T_e} of the density and temperature of the free electrons. Taking the values $T \ll T_{\text{кр}}$, $T_{\text{кр}} \simeq 0{,}1 \div 0{,}2$ eV and and taking into account the fact that the energy of formation of a pair of molecular ion-free electrons in the plasma constitutes $E_{\text{пар}} \simeq 10 \div 30$ eV, we see that the quasi-stationarity is already ensured for $\alpha \sim 10^{-4}$. The quasistationary solution of equation (2) with the substitution of the existing temperatures of gas and electrons will give a clearly nonequilibrium value $N_e = N_e^0 (1 + \eta)$ since the term zG

determines a nonzero flow of electrons inserted into the gas by means of ionization, as if from the side. Another reason for nonequilibrium, the difference in the temperatures of the electrons and solid particles, has less effect on the quantity N_e. We will estimate the quantity η of the relative deviation (caused by the nuclear fragments in the gas which fills the EDEL) of the density of free electrons from its thermodynamic equilibrium value N_e^o. By setting $G = 0$ in (2) we determine the value N_e^o itself. The quantity N_e^o corresponds to equilibrium with existing values of the density of the gas N and the temperature of the electrons T_e[3] in the given plasma:

$$K_e N_e^2 = SN. \tag{2a}$$

Furthermore, by (2) we have

$$\eta = \frac{1}{2}(\sqrt{1+\beta} - 1), \quad \beta \equiv 4\frac{zGK_e}{S^2N^2}. \tag{5}$$

Since the parameter β is positive, in the problem being discussed we always have $\eta > 0$, i.e., the plasma is in recombination nonequilibrium (overionized, or equivalently, supercooled). The value of the dimensionless parameter β characterizes the degree of the recombination equilibrium. Formula (5) shows the simple connection between this parameter and the relative deviation from equilibrium of the density of electrons supported by a rigid source in quasistationary conditions. In particular,

$$\eta \simeq \beta/4 \quad \text{for} \quad \beta \ll 1, \quad \eta \simeq \sqrt{\beta/4} \quad \text{for} \quad \beta \gg 1. \tag{5a}$$

The relation $B \gg 1$ is a condition for intensive volume recombination of the plasma. If it holds, then

$$N_e \simeq N_e^o \eta = \sqrt{\frac{zG}{K_e}}, \tag{5b}$$

i.e., the term SNN_e, which determines the ionization rate of the gas by eigen electrons, need not be taken into account in equation (2). It is clear that this affects not only the electron density, but also the populations determined by the value N_e. The physical conditions for this are formulated direction from equation (5) for β.

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*The value of the gas temperature, as determined by N_e^o, would have to be set equal to the electron temperature ($T_e = T$) but in practice this would have no effect on the parameters S, K_e, z.

for sufficiently high energy intensities of the source of external ionization and a low temperature of free electrons** we may assume that these eigen electrons*** of the plasma do not ionize molecules but only recombine, compensating for that "side" ionization of the gas.

THE COMPOSITION AND PARAMETERS OF THE ACTIVE MEDIUM [4]

We will now discuss general regularities of the formation of the inversion of populations of discrete levels of atoms (molecules, ions) in an intensively recombining plasma. We will begin with the fact that nonelastic collisions between heavy particles and electrons affect the populations of the excited levels in overionized plasma with a sufficiently high concentration of free electrons ($N \gtrsim 10^{14}$ см$^{-3}$). Under these conditions, the most likely collision transitions are those between energetcially close states of a particle where the difference in energies does not exceed the electron temperature. Due to the effectiveness of such transitions in the distribution of discrete levels, local "blocks" are separated out. Inside each of these the populations obey the Boltzmann law. That is, there is a common population within a given block, and the effective temperature is the same for all blocks. This temperature is equal to the temperature T_e of the free electrons of the plasma. Taking this into account simplifies the analysis of the relaxation of the populations. In the first stage of this calculation, the closely arranged energy levels are united into single states (blocks) with populations $N_{(M)} = \sum_{m \in M} N_m$ (which are total for each flock) and statistical weights $g_{(M)} = \sum_{m \in M} g_m$ (Figure 1). The populations are computed of the system formed in this way of a much lower order. It is simpler than the analyzed atom. The energy levels in it are spaced comparatively far apart from each other. In the second stage of this calculation, the settlements of

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**By what we have said above (Formula (3)) the low (for free electrons of appreciable density) temperature $T_e \leq 1$ eV with a sufficient density N of the gas is supported by the cooling against solid particles of gas.

***A side source of gas ionization in a wide variety of problems of the type discussed here does not mean nuclear fragments, but rather electrons of some external source which has been introduced, for example.

individual levels within the block are found easily by the Boltzmann formula.

Of particular interest is the band of closely lying energy electron levels adjacent to the continuous spectrum of (free) electrons. The populations of such levels relaxes at a rapid rate, as it is filled by the recombination flow directly from the electron continuum. Because of the proximity of these levels, the rate of the flow here is determined by transitions due to the action of the collisions of free electrons. As the energy of the state of the atom is lowered, the rate of the collision relaxation falls, but in general, the probability of its spontaneous radiation de-excitation increases. Furthermore, under the defined conditions, the collisions of heavy particles among themselves influence the excited states, often leading to a refinement - a sharp decrease of the populations. An inversion of the populations of these or another pair of levels arises in such a situation, allowing for the amplification of radiation on the transitions between them.

In the laser-active medium, let the amplification of light take place on the transition X(a) → X(b) of the atom (molecule, ion) X. Such a transition is called "working".

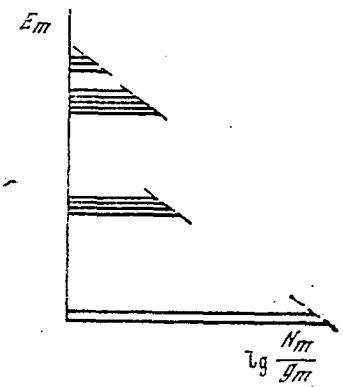

Fig 1

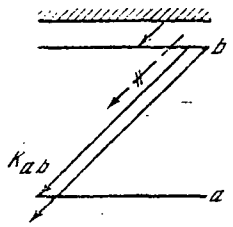

Fig. 2

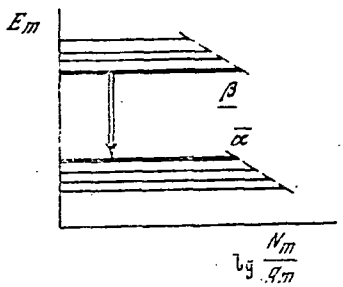

Fig 3.

We will denote respectively by the indices a and b the characteristics of its lower and upper "working" levels, with energies E_a and E_b, $E_a < E_b$. Due to the inversion of the populations of these levels $N_a/g_a < N_b/g_b$ by means of induced radiation transitions $X(b) + \hbar\omega_{ab} \rightarrow X(a) + 2\hbar\omega_{ab}$ in the medium, radiation of frequency $\omega_{ab} = 1/\hbar\,(E_b - E_a)$ is amplified at low intensities J of such radiation, its passage

through the laser medium has, in practice, no effect on the populations. This same radiation strengthens its intensity in proportion to the path it takes through the medium:

$$dJ = J\varkappa_0 dz, \quad \varkappa_0 = \sigma_{ab}\left(N_b - \frac{g_b}{g_a}\right)N_a = \sigma_{ab}N_b(1 - \delta_{ab}), \tag{6}$$

where σ_{ab} is the cross-section of photoabsorption on the working transition, $\delta_{ab} \equiv \frac{g_b N_a}{g_a N_b}$ is the inversion coefficient, and $\varkappa_0$ is the coefficient of unsaturated amplification. With an increase in intensity, the population of the working level falls and the population of the lower increases. When the amplification coefficient decreases, "saturation" takes place. Under conditions of practically complete saturation $J \gg J_н$, the medium is almost transparent.

$$N_b - \frac{g_b}{g_a}N_a \ll N_b, \quad \varkappa \ll \varkappa_0.$$

Under these conditions, the amplification of the light is proportional to the path taken and no longer depends on the field intensity: dJ = Cdz. We are interested in questions concerning the preparation of the laser-active medium, and will not at this time consider the influence of the amplified light on the population. We will only consider spontaneous radiation transitions. We will examine the simplest method for amplified light, the "open two-level model". We will assume that there are no intermediate levels between the working levels, that the energy difference $E_b - E_a$ is not small, and that we need not consider transitions which go past the state b (the dotted arrow in Figure 2) in the recombination flow of electrons which flows from the continuum to discrete levels. Then the equations for the populations of the working levels are represented in the form

$$\frac{dN_a}{dt} = K_{ab}N_b - K_a N_a, \quad \frac{dN_b}{dt} = \frac{N_+}{\tau_+} - K_b N_b. \tag{7}$$

Here K_a, K_b, K_{ab} are the kinetic coefficients, and N_+, τ_+ are the concentration and characteristic lifetime of the ions X^+. In a wide class of questions, the "stationary drain" conditions hold: the rates of changes of populations of the working levels are small by comparison, with the partial rates both of their filling $K_{ab}N_b$ and $N_+\tau_+$ and of their refining $K_a N_a$ and $K_b N_b$. Thus, in estimating the populations of the working levels, we can set $dN_a/dt = dN_b/dt = 0$. Then the inversion condition which the kinetic coefficients must satisfy takes the form

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$$\delta_{ab} = \frac{g_b K_{ab}}{g_a K_a} < 1. \qquad (8)$$

We also obtain from (7) the simple formula for the population of the upper working level

$$N_b = 1/K_b \, N_+/\tau_+. \qquad (9)$$

If instead of the two energy isolated states a and b, the atom X has blocks of closely lying levels $(\alpha_1, \alpha_2, \ldots, \alpha_p)$ and $(\beta_1, \beta_2, \ldots, \beta_q)$, $E_\beta - E_\alpha \gg |E_{\alpha'} - E_{\alpha''}|, |E_{\beta'} - E_{\beta''}|$, then equations of the form (7) determine the kinetics of the total population of these blocks. In such a case it is usually appropriate to choose the most populated lower level $\underline{\beta}$ of the block $(\underline{\beta})$ as the upper working level, and take the emptiest upper level $\bar{\alpha}$ of the block (α), as the lower working level. The condition for the inversion of populations at the transition $\underline{\beta} \to \bar{\alpha}$ can be much milder than what is written according to (8) for the total population of the blocks (α) and (β); this is explained in Figure 3.

The disintegration of the supercooled plasma can begin with various acts of recombination: the three-particle ($X^+ + e + Z \to X^* + Z$) the dissociative ($XY^+ + e \to X^* + Y$). the ion-ion ($X^+ + Y^- \to X^* + Y$) or $X^+ + Y^- + Z \to XY^* + Z$), the supercharged ($X^{++} + Y \to (X^+)^* + Y^+$), etc. They all lead, with an overwhelming probability, to the filling of the highly excited electron states of the atom (molecule, ion) which is produced in the initial stage of relaxation. We can thus say that the recombination of plasma is the universal mechanism of the "pumping" of the upper working level; the more intensively recombination goes on, i.e., the greater the quantity N_+/τ_+, then by formula (9), the higher the population N_b of this level. The amplification coefficient x increases proportionally to N_b and thus to the relation N_+/τ_+, it is necessary only that condition (8) for the inversion of the populations be satisfied. This condition is ensured if the rate K_a of refinement of the lower working level is sufficiently high. The mechanisms of refinement must be examined on a more individual basis, as they function according to different principles. The possibility of their operation and the effectiveness depend both on the general conditions (the values N, N_e, T, T_e), and on the chemical composition of the plasma. The simplest and most general mechanism of refinement is determined by the spontaneous radiation

disintegration of the lower working level

$$X(a) \rightarrow X(0) + h\omega_{0a}. \qquad (10)$$

In a short discussion it is not necessary to discuss specifically the refinement of the excited state in the course of collisions with free electrons of the plasma. We have already noted that the formation (in the distribution of populations of discrete levels) of blocks of closely lying states, inside which locally - Boltzmann regions of the distribution are rapidly established, is a result of such a process. The refinement of excited levels during collisions between heavy particles comes about usually either by means of the ionization of an easily ionized impurity by an excited particle of an atom or molecule in acts determined by the Penning effect:

$$X^* + Y \rightarrow X + Y^* + e \qquad (10a)$$

or by the particles passing into a chemical reaction, for example, such as

$$X + Y + Z \rightarrow XY + Z, \quad X + YZ \rightarrow XY + Z \qquad (10b)$$

It is essential that the chemical reactions be able to make use of particles (atoms, molecules, ions) not only from the excited states but also from the basic electron state. We can point out two methods in addition to the electron excitation method for refining the basic states. In the case of the ion, it is to recombine it into a neutral particle (or an ion with a smaller charge).

$$X^+ + e \rightarrow X^*,$$

but in the case of a thermally unstable or even scattered molecule XY the refinement of its term of this type proceeds with the separation of the molecule into fragments:

$$XY \rightarrow X + Y \qquad (10c)$$

In order that the energy of nuclear fission be effectively carried out of the atomic reactor in the form of directed light, it is necessary to set up a series of conditions, of which we mention two: 1) the range of energy of the working transitions of the medium passing into radiation must be close to the ionization potential of the "working" atoms (molecules); 2) the intensity of the radiation at these transitions within EDEL must be sufficiently great so that we can neglect acts of spontaneous de-excitation in comparision with acts of induced transitions.

This last statement indicates that EDEL, each individually or taken collectively, must ensure the sufficient amplification of light. The threshold value of the amplification coefficient which compensates for the loss of working radiation in the medium and in the resonator, is estimated by the quantity for which $\exp(\varkappa_{пор} L) = 1/\xi$, where L is the length of the active medium and ξ is the fraction of intensity lost by the light in the resonator as it passes through once. If $\xi \ll 1$, then.

$$\varkappa_{пор} = 1/L\,(\ln(1+\xi) \simeq \xi/L. \tag{11}$$

The value $\varkappa_{пор}$ can serve here only as some reference point, since the intensity of its radiation is too small on the threshold of self-excitation of the laser. As has been noted above, the amplification coefficient falls with an increase of J. Therefore for the effective operation of an RL it is necessary to ensure a much stronger pumping of the upper working state, at least 1-2 orders of magnitude higher than its threshold value. Since we are not discussing at this time specific mechanisms of relaxation and the chemical composition of the chosen active medium, we will assume beforehand that the effective refinement of the lower working level allows us to ignore its population and to assume that $\delta_{ab} = 0$. We find the threshold value $W_{пор}$ of the energy intensity of the reactor laser in quasistationary working conditions from formula (2) with $SNN_e \simeq 0$. Having obtained

$$N_+/\tau_+ = K_e N_e^2 = zG,$$

we substitute this equality together with the condition $\delta_{ab} = 0$ into formula (6). Equation (12) follows from this for the number of fissions

$$G_{пор} = \frac{K_b \varkappa_{пор}}{\sigma_{ab} z} = \frac{K_b \xi}{\sigma_{ab} z L}. \tag{12}$$

The cross section σ_{ab} of the photoabsorption at the working transition can be represented in the form $\sigma_{ab} \simeq \frac{\lambda_{ab}^2}{4} \frac{A_{ab}}{\Delta\omega_{ab}}$, where $\Delta\omega_{ab}$ and λ_{ab} are the frequency width and the wavelength of the line of this spontaneous transition $b \to a$; A_{ab} is its probability. The width of the line under the conditions we are discussing, as a rule, is formed by the Doppler effect and therefore we can set $\Delta\omega_{ab} = 10 \frac{v_T}{\lambda}$ where $v_T = \sqrt{2M/T}$, is the thermal rate of the heavy particles which amplify the radiation.

Taking this into account, we write

$$G_{\text{пор}} = \frac{1}{Lz} 40\xi \frac{v_T}{\lambda_{ab}^3} \frac{K_b}{A_{ab}}. \qquad (12a)$$

The total probability K_b of the disintegration of the upper working level of the active medium is computed from the probability of a spontaneous radiation transition to the lower working level, as well as to all remaining energy levels of the "working" particle X, which lie below b, and thus from the probabilities of collision transitions from level b, occurring at all states of this particle during its collisions with electrons and heavy particles, and finally from the probability of X(b) entering into chemical reaction. If the densities of both the free electrons and the impurities to the working particles X are comparitively small, then the probability of the disintegration of the upper working level is minimal and is determined only by the spontaneous de-excitation. Often in this case, we can take into account only the radiation working transition, since the remaining spontaneous transitions from the upper working level turn out to be weakened from the reabsorption of radiation in the dense gas. Having denoted by $G_{\min}$ the minimal threshold frequency of nuclear reactions corresponding to this situation, we write $K_b \simeq A_{ab}$, and then

$$G_{\min} = 40\xi \frac{v_T}{zL\lambda_{ab}^3}, \quad W_{\min} = G_{\min} E_{\text{дел}}. \qquad (13)$$

It is evident from these formulas that the effectiveness of the light channel for the extraction of energy from an RL (just as the effectiveness of the condition for amplifying radiation in any optical quantum generator) is determined by the density J of the total pumping through the cross section perpendicular to the direction of the flow of radiation leaving the optical resonator. In our case $J = WL$ where W is, as before, the energy intensity of the reactor, the power of the pumping which is released in 1 cm^3 of the amplifying medium. For the minimal value of the threshold intensity by (13) we have

$$J_{\min} = W_{\min} L \simeq 40\xi \frac{v_T}{\lambda_{ab}^3} E_{\text{дел}}. \qquad (14)$$

To estimate the orders of magnitude of the quantities which arise here, we will now give some numerical values for the parameters of

the active medium. For example, let $\xi = 0.1$, $z = 1 \cdot 10^7$, $E_{нар} = 20$ eV, $\lambda_{ab} = 4000$ Å, $v_t \simeq 10.5 \text{cm/sec}^{-1}$. The following minimal values for the rates of fission and energy intensity correspond to the three values of length $L^{(1)} = 2\text{m}$, $L^{(2)} = 10$ m, $L^{(3)} = 50$ m of the active medium of an EDEL:

$$G_{min}^{(1)} = 4 \cdot 10^9 \text{ fissions} \cdot \text{cm}^{-3}, \quad W_{min}^{(1)} = 0.1 \text{ watts} \cdot \text{cm}^{-3},$$

$$G_{min}^{(2)} = 8 \cdot 10^8 \text{ fissions} \cdot \text{cm}^{-3}, \quad W_{min}^{(2)} = 0.02 \text{ watts} \cdot \text{cm}^{-3},$$

$$G_{min}^{(3)} = 1.6 \cdot 10^8 \text{ fissions} \cdot \text{cm}^{-3}, \quad W_{min}^{(3)} = 0.004 \text{ watts} \cdot \text{cm}^{-3}.$$

These three lengths correspond, of course, to the same threshhold intensity of fission $J_{min} = 20 \text{ watts} \cdot \text{cm}^{-2}$. From what we have said above it is clear that the values obtained here, which are very modest for atomic reactors, are rough, low estimates. So under RL conditions, the rate of collision and chemical refinement of the upper working level will, in general, exceed the rate of spontaneous radiation disintegration of this level. In relation to this, the true threshold intensity of the pumping $J_{нор}$ can exceed J_{min} by a factor of ten or more, which, nevertheless, does not make the value of the intensity $J_{нор}$ too high. For more basic calculations, we must turn to the discussion of specific compositions of gas mixtures and thermal conditions within EDEL.

The extraction of a considerable fraction of the energy of nuclear fragments in the form of light can moderate the thermal operating conditions of the work of an atomic reactor. In roughly estimating here the critical temperature characteristics of RL, we will assume for simplicity that in EDEL all energy from the fission of uranium nuclei escapes in the form of heat. It is necessary to examine the thermal operating conditions of RL's for three reasons. In the first place, the free electrons must be sufficiently cold, since only with the great supercooling is the intensive recombination pumping onto the upper working level X(b) possible; here, heavy particles of gas are a cold thermostat which allows for the cooling of free electrons. In the second place, raising the temperature of the gas (and of the electrons) higher than a certain characteristic critical value for a given chemical composition of the active medium leads to the breakdown of the mechanisms of plasma relaxation which

ensure the refinement of the lower level. We will illustrate this with several examples. It is clear, for example, in the collision of heavy particles X with electrons leading to the establishment of local Boltzmann distributions in blocks of closely spaced states. When T_e of the electron temperature rises, settlements within the blocks are leveled, eliminating this mechanism of effectiveness. Raising the temperature of the gas T slows the rate at which particles enter into chemical reactions of the type (10b), because of the shift of the constant of equilibrium to the side of the inverse reaction. In the case of the scattering reaction (10b) with an increase in the temperature T there is an increase in the number of fragments X and Y having sufficiently high energy, so that - along with the working transition of photodissociation $(XY)^* \to X + Y + h\omega$ - with an appreciable probability photoassociative acts can occur with absorption of energy of the working frequency [2]. The third reason for limiting the temperature of EDEL is of a technological nature, traditional for atomic reactors.

With a sufficiently high gas density (it is assumed $N \gtrsim 3 \cdot 10^{20}\ см^{-3}$) and a low degree of its ionization, the temperature of the electrons exceeds the gas temperature. Consequently, for the effective amplification of light, we need to ensure a sufficiently low gas temperature in EDEL. Not detailing the specifics of various chemical compositions of the active medium, we will start with a rough estimate $T < 3000°K$. We will estimate the corresponding limitation of the steady-state energy intensity of the reactor when the gas filling the EDEL is cooled only at the expense of its molecular thermal conductivity to the walls of these elements. The walls are effectively cooled by the coolant, which ensures a stationary gas temperature T in the center of the EDEL. Here it is assumed that the cylindrical EDEL of comparitively great length is cooled by the flow of the coolant, which is being forced to circulate, and that the flow rapidly carries away the heat. Taking formula (4) into account, we write

$$Q = \frac{N}{\tau_{охл}}(T - T_0), \quad \tau_{охл} \approx \frac{R^2}{4\chi}, \tag{15}$$

where $\tau_{охл}$ is the characteristic cooling time of the gaseous active medium located in the cylindrical container (of the EDEL), χ is the

thermal conductivity of the medium, R is the radius of the container, and T_o is the temperature of its walls. Limiting ourselves here to rough estimates, we will not take into account the nonuniform distribution of the gas-phase nuclear fuel within the EDEL. This nonuniformity is determined by the large temperature gradient along the radius. (The nonuniform density of uranium leads to the dependence of the number of nuclear fissions, and thus the heat released, on the radius within the EDEL; this same role is also played by the dependence of the reaction of uranium nuclei with electrons on the gas temperature). We set $\chi = v_T/\sigma_{упр}N$, where $\sigma_{упр}$ is the cross section of the elastic scattering of atoms (molecules) of the gas which fills the EDEL, and by formulas (4) and (15) we represent the stationary temperature of the gas in the form

$$T = T_0 + \frac{W}{N}\tau_{охл} = T_0 + W\frac{R^2\sigma_{упр}}{4v_T}. \qquad (16)$$

Using this last equality, we estimate $W_{кр}$, the maximum permissible energy intensity of the RL with which permissible (for the effective amplification of light) stationary temperature operating conditions are still ensured

$$W_{кр} = \frac{4(T_{кр} - T_0)v_T}{\sigma_{упр}R^2}. \qquad (16a)$$

Having set $T_{кр} - T_0 = 0{,}2$ eV $\sigma_{упр} = 10^{-15}$ см^2, $R = 1{,}5$ см, $v_T = 10^5$ см·sec^{-1} in formula (16a), we obtain

$$W_{кр} \approx 4\cdot 10^{19}\,\text{eV}\cdot\text{см}^{-3}\cdot\text{sec}^{-1} \approx 5\,\text{watts}\cdot\text{см}^{-3}. \qquad (17)$$

This quantity corresponds to the maximum permissible rate of nuclear fissions $G_{кр} \simeq 2\cdot 10^{11}$ fissions · cm^{-3} · sec^{-1}. In a reactor on thermal neutrons with a gas-phase fuel, containing a concentration $N(U^{235}) \simeq 3\cdot 10^{19}$ cm^{-3}, the quantity $G_{кр}$ corresponds to a flow of neutrons on the order of $10^{13} \div 10^{14}$ neutrons · cm^{-2}sec^{-1}. We must note that the critical energy intensity (17) that we have given has a considerable margin of error. The calculation of the dependence of the radial distribution of the heat release intensity on the gas temperature will lead to a considerable increase in the permissible value of the energy intensity. Still more important is the margin of error in (17), connected with ignoring the possibilities for a more rapid removal of heat from the central part of the EDEL by means of

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natural convection or forced radial circulation of the fuel.

But what must the chemical composition of the active medium of an atomic RL be? To begin with, uranium hexaflouride must be part of the gas filling the EDEL mainly because its boiling point $T_{кип} \simeq 70^{\circ}$ C is minimal, among all known possible uranium compounds. It is also essential, in analyzing the possibilities of its laser use, that the gas UF_6 be transparent in the visible band. We must add a sufficient concentration of flourine impurities to the medium so that the problem is not complicated by the compounds UF_4 and UF_2 released from UF_6 and settling on the walls of the EDEL. If it were clear that the mixture $UF_6 + F_2$ ensured laser activity with a high conversion efficiency of energy (consumed in its ionization) into energy of light extracted from EDEL, we would decide at this time on such a composition for the gas filling the EDEL. But the properties of hexaflourine in this regard have not been studied at this time. Therefore, it is necessary to analyze at this time several examples of chemical compositions of the gas in which the specified component other than UF_6 and F_2 ensures laser activity. A requirement which must be imposed on such a component, of course, is that it be chemically passive with respect to UF_6 and F_2. We could take, for example, inert gases of flourides whose boiling points are not too high for such a component.

The amplifying possibilities of media which are suitable both in terms of their chemical composition and their plasma parameters for effective use in EDEL, unfortunately, have not yet been analyzed in any detail. Nevertheless, it is possible at this time to form a general impression of the expected characteristics on the basis of works, carried out for different variants of recombining plasma. First of all we must mention numerical estimates of the characteristics of the stationary amplification of light in an EDEL which is filled with a mixture of helium and uranium hexaflouride and flourine. Here we had in mind the use of radiation with transitions of helium atoms between the states He ($n = 3$) → He ($n = 2$) or of helium molecules between the correlated (with given states) electron terms of a molecule He_2. These transitions shut off only a small fraction of the ionization potential of helium, and therefore the coefficient for conversion into directed light of the energy of the ionization of such plasma is very small.

Such an active medium need not be examined as one of the variants for filling an RL, but is of interest for the development of certain general features which characterize the problem of amplifying light under the action of nuclear fragments. Even now this medium is comparitively accessible for theoretical examination; it is perhaps simpler in this case than in the case of media of other chemical composition to carry out model control experiments. The mechanism of forming the necessary populations on the working levels in this case is the following: pumping onto the upper level is determined by the recombination of helium ions. The refinement of the lower working level is connected basically with de-excitation by Penning collisions (mainly with UF_6 molecules):

$$He(2) + Z \rightarrow He(1) + Z^+ + e$$

or

$$He_2(2) + Z \rightarrow He(1) + He(1) + Z^+ + e.$$

The estimates [4] attest to the possibility of starting a laser of length L ≃ 30 m on such an active medium with densities N (He) ≃ $3 \cdot 10^{20}$ cm^{-3}, N (UF_6) ≃ $3 \cdot 10^{19}$ cm^{-3}, 90% absorption of uranium a radius of EDEL pf R ∿ 1 cm, and a common diameter of the reactor of ∿1 $м^2$. More precisely, the estimates show that with this choice of parameters, the condition $G_{кр} > 2G_{пор}$. is satisfied. This examination also points to the desirability of lowering the concentration of the component UF_6 by approximately one order of magnitude with this choice of the chemical composition of the medium. The lowering here of the quantity N (UF_6) will lead to several consequences. To begin with, the rate $K_в$ of refinement is lowered during ionizing collisions of the upper working state He(3). This is precisely the basic goal in lowering N (UF_6). The rate $K_а$ of the refinement of the lower working state He(2) is, of course, also somewhat lowered, which will lead neither to the collapse of the inversion on the working transition nor to a noticeable drop in the coefficient of unsaturated amplification. The slowing of the refinement of the upper working level thus allows us, without lowering the coefficient of amplification, to reduce the recombination flow (and thus the density of free electrons and the intensity of fission) and at the same time,

reduce the heating of the amplified medium. But to ensure the criticality of the reactor in terms of neutrons, it is necessary in this case to change to the corresponding increase of the transverse dimensions of the RL (i.e., in the simplest case of a RL with parallelly positioned elements, to change to an increase of their number, Figure 4).

We must note that in these comparatively rare variants of the active medium of plasma lasers, for which, along with a calculation of the relaxation, laboratory studies are also available, the theory rather well agrees with experiment. This is true, first of all, in regard to results from calculating the characteristics of light amplification in disintegrating plasma at transitions of ions of alkali-earth elements and the successful start-up of pulse lasers in such a plasma [5]. The available information indicates a good agreement between theoretical [6] and experimental [7] works which deal with the generation of radiation for transitions of dimeric molecules of inert gases from connected electron-excited states to a basic repelling term. The disintegrating plasma in such works is obtained by the introduction of a beam of fast electrons into a dense, inert gas of high chemical purity. Unfortunately, the experience with these two types of plasma lasers cannot be

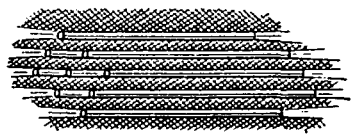

Figure 4

directly transferred to the problem of starting RL. The amplification of light at transitions of ions or in a chemically pure inert gas cannot be achieved in the medium which fills EDEL.

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EXAMPLE OF THE ACTIVE MEDIUM OF A STATIONARY RL [8]

The nature of relaxation processes in a vigorously recombined plasma having a carefully selected composition is favorable for the amplification of fluxes of high energy light. According to rather general considerations and calculations, under conditions of a supercooled plasma in principle it is possible to plan for the transfer of ionization energy into the energy of directional radiation with a high coefficient $\eta \sim 0{,}7 \div 0{,}8$. In order to explain this, we note that the upper working level in such a plasma comprised of the electron continuum may be located rather close to the ionization boundary. The lower working level in the decomposed plasma may lie close to the minimum energy of the basic state of the working particle (atom, molecule). The best example of this is the successful generation of photodissociative radiation of scattered molecules at the transition at which the lower working "level" occupies a comparatively low energy range in the basic (here — repulsed) electron term. We should note that in this case the purification of the lower working state is carried out apparently by the most rapid of the chemical reactions — during the separation of molecule fragments in the repulsed term. It is not possible to use the generation of radiation in such transitions of the scattered molecule, primarily due to the smallness of the section σ_{ab} (photoabsorption at the working transition) connected with the unusually wide frequency band of the corresponding line of luminescence encompassing $\Delta\omega \sim 10^{14}$ sec^{-1}. Due to this, it is possible to achieve the range of amplification coefficient values which are necessary for using laser generation in EDEL (and also for obtaining the effective removal of energy by laser emission) only for very large populations of the upper working level. Those values of N_b now obtained experimentally by ionization of a dense gas by a high current relativistic

beam of electrons exceed by several orders of magnitude the values used in traditional laser technology. For any methods of gas ionization with this type of regime, it is necessary to perform intense injection of energy and rapid heating of the gas itself. In the experiments mentioned here with amplification by photodissociative transitions of the scattered molecules in the basic state

$$XY(2) \rightarrow X(1) + Y(1) + h\omega_{12} \qquad (18)$$

Overheating of the gas above the critical temperature T_{kp} occurs / 11
in the time $\Delta t \sim 10^{-7} \div 10^{-6}$ sec. At temperatures of $T > T_{кр}$ there already are many rapid atoms in the gas, for which the inverse (18) photodissociative act is achieved

$$X(1) + Y(1) + h\omega_{12} \rightarrow XY(2),$$

so that the medium is not amplified, but absorbs light at these frequencies.

The more general conclusion may be drawn from the above statements regarding the advantage of selecting strong radiation transitions as the working transitions, with very narrow luminescent lines, under the conditions of a stationary RL. It is natural to try and solve the problem in the most radical way, concentrating the discussion on an analysis of the possibilities of light amplification in the mixture filling the EDEL in atomic transitions. We shall select the basic or lower state of the X atom as the lower working level. We shall try to use its levels lying close to the continuum as the upper working level. This is important for obtaining a high coefficient for the conversion of energy into light, but the power of the oscillator at such transitions and the photoabsorption cross sections decrease with an increase in the basic quantum number. At first it appears that an analysis of these possibilities is difficult without specifically selecting the chemical element X, in view of the fact that there are too many equivalent variations. However, this is not the case. The number of suitable elements X is unfortunately very limited. Thus an analysis must take into account several factors, including the important calculation of the transmittance of all the mixture components at the working

transition. It may be expected that this aspect of the problem does not lead to great limitations, since the transition of the X atom from the higher state to the basic state (or that adjacent to it) may be effectively divided, as a rule. For sufficient population of the level b and inversion at the transition b → a, if its frequency ω_{ab} is too large for any of the components (but there is an intermediate level c such that $E_b > E_c > E_a$,), then in order to use amplification at the frequency ω_{ab} we must change to longer wave emission at frequencies of ω_{ac} and ω_{cb}. It is possible to use not only biquantum, but also multi-quantum partition of the working transition. In a dense, comparatively cold gas, how can we obtain sufficient concentrations of atoms of the necessary type? It would appear that in a gas mixture containing fluorine and hexafluoride of uranium, there may be only inert gases among all of the chemical elements. The latter, as is known, associates into molecules in excited states when they are very dense.

In view of the statements made above, for a unique solution of this problem, it is necessary to consider the set of plasma processes, during which atoms arise from molecular compounds during their ionization in excited states. The atoms go into a chemical reaction as recombination relaxation takes place, forming the initial compounds. If the binding rate of the working atoms of X in their basic state is high enough, then it is possible to calculate the inversion of the populations of this atom in the transitions either in this state, or in the state adjacent to it in terms of energy. In order to have the necessary binding rate, it is necessary to find the corresponding chemical reaction of the element X with a large cross section and, in addition, to have a high concentration of the component Y reacting with X. We find it necessary that the predominant part of the plasma ionization energy go into the formation of excited atoms X*. Therefore the density N(XZ) of the X* component produced must be at least one order of magnitude higher than the concentration of the remaining components. Since we have already used the condition $N(UF_6) \gtrsim 10^{19}\ см^{-3}$, it may be concluded that here we must consider the concentrations of $N(XZ) \gtrsim 10^{20}\ см^{-3}$. It follows that the compounds XZ must be

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sufficiently volatile — in other words, such a concentration is not obtained at moderate temperatures of $T < T_{кр}$. These considerations, along with the previous considerations regarding the requirements for the components of the medium filling the EDEL, greatly reduced the possible variations. At the present time we feel that the most suitable atom for amplifying the emission in a stationary RL is thalium and its compound (one of the basic compounds in terms of the concentration of the components of the mixture filling the EDEL)— thalium fluoride (see below [9]). /117

We shall thus assume that this mixture contains three components of the following concentrations

$$N(\mathrm{TlF}) \sim 3 \cdot 10^{20}\ см^{-3},\ N(\mathrm{UF_6}) \sim 3 \cdot 10^{19}\ см^{-3},\quad N(\mathrm{F_2}) \sim 10^{19}\ см^{-3}.$$

Relaxation begins when the rapid electrons of the "cascade" (which are produced during flights in the medium of uranium fission fragments) lead primarily to the appearance of molecular ions and excited molecules of thalium fluoride. The thermal density of the molecular ion $(\mathrm{TlF})^+$ is very low. The depth of its basic electron term is only two thousands of degrees: $D(\mathrm{TlF})^+ \simeq 0{,}2$ eV. The same holds true with respect to higher electron-excited states of the neutral molecule $(\mathrm{TlF})^*_{эл}$. . The thermal decomposition of the ion $(\mathrm{TlF})^+$, three-part recombination of $(\mathrm{TlF})^+$ or Tl^+, and also disassociative recombination $(\mathrm{TlF})^+$ and mixing of the channels of recombination relaxation Tl* and $(\mathrm{TlF})^*_{эл}$ — all these acts must be reduced to the great predominance of thalium atoms among the electron-excited particles of the gas filling the EDEL.

The reaction cross section

$$\mathrm{Tl}\,(m) + \mathrm{F_2} \rightarrow \mathrm{Tl\,F}\,(m) + \mathrm{F} \qquad (19)$$

with a fluorine molecule of the unexcited thalium atom m = 1 belongs to the largest cross section of binary chemical reactions $\sigma_{хим} \sim 10^{-14}\ см^2$. The great depth of the basic term of thalium fluoride $D(\mathrm{TlF}) \simeq 4{,}6$ eV makes it very unlikely that inverse (19) acts will occur in which excited thalium atoms are restored. The situation is different with electron-excited molecules, at least with those whose energy is close

to the ionization energy of the molecule J (TlF) $\simeq$ 6 eV. The terms of these molecule states comprise in all several tens of eV. With a gas temperature which is necessary for the $N(\mathrm{TlF}) \sim 3 \cdot 10^{20}$ $см^{-3}$ concentration, such rapid inverse (18) acts of restoring the molecule of the excited atom Tl(m) make the chemical purification of such levels m > 1 of thalium ineffective even for comparatively high probabilities of collision transitions. With a fluorine concentration of $N(F_2) \sim 10^{19}$ cm^{-3}, it is important that the purification rate of the state Tl(1) by the chemical reaction (19) be sufficient, not only for the inversion of the populations, but also for effective amplification of light and several transitions of the thalium atom in the state $6P^2_{1/2}$, particularly from the levels 8S and 7D.

The scheme for obtaining excited thalium atoms during ionization of a molecular gas by nuclear fragments and the outflow from the gas of the atoms in the basic state is incomplete, since the initial and final stages do not coincide. The cycle of thalium is not closed — ionization occurs primarily from the lower oscillatory levels of the basic term of the molecule, and after relaxation of the thalium atom (which includes emission at the working transitions) and the participation of Tl (1) in a chemical reaction (19), the molecule is formed in the basic electron term, but at the excited oscillatory-rotational levels (Figure 5). Since the depth of the potential hole of the basic term is not small as compared with the ionization potential, the problem arises of the nature of relaxation of the molecules thus produced. If all of the energy D (TlF) of the basic term passes into heat, then the coefficient for conversion of ioniza- / 118
tion energy into emission does not exceed 50% even in the best variation of relaxation, which can barely be implemented.

The linear flux, which takes place according to the act (19) of the binary chemical reaction or during the trinary collisions of the type $\mathrm{Tl}(1) + \mathrm{F}(1) + \mathrm{Tl\,F} \rightarrow (\mathrm{TlF})^{*}_{\text{кол}} + \mathrm{TlF}$, leads to the formation of molecules at the high oscillatory levels: we may speak here of a supercooled nonuniformally dissociated gas. Relaxation in terms of oscillatory levels of the deep term in this case may produce inversion

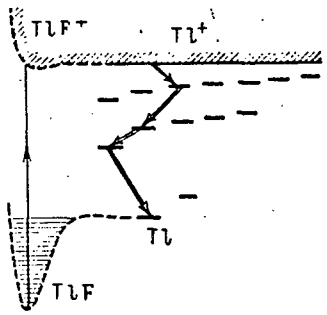

Figure 5.

of the populations in the whole chain of oscillatory-rotational transitions. This is due to the great density of the energy which occupies the oscillatory degree of freedom during the association of thalium into the molecule, whereas the molecule rotational energy rapidly is equalized with translational degrees of freedom of the cold gas. In addition, as was shown in [10], under such conditions, absolute inversion (without a change in the rotational state) is produced in a large portion of the oscillatory transitions. Thus, in order to determine how high may be the coefficient for conversion of fragment energy into emission from the EDEL, in a given 3-component gas mixture TlF + UF_6 + F_2 along with analyzing the electron working transitions of a thalium atom, it is also necessary to analyze the effectiveness of amplification at oscillatory-rotational transitions of a molecule of thalium fluoride.

PULSE SCHEMES OF THE REACTOR-LASER [11]

It is clear that, other conditions being equal, the possibility of greatly increasing the frequency G of nuclear fissions simplifies the problem of starting an atomic reactor, makes it possible to produce more intense emission, improves the characteristics of light amplification in EDEL, makes it possible to expand greatly the selection of the possible active media, and makes it possible to construct RL of comparatively small lengths (in general it makes the technical equipment simpler, improves the basic RL characteristics and makes them more diverse). This illustrates the importance of examining the characteristics of RL operation in overloaded pulsed modes, for which a very high energy intensity is characteristic for small time intervals $\tau_{имп} \sim 10^{-6} \div 10^{-4}$ sec. When such equipment is built for scientific research, it is possible to keep in mind the operation with individual pulses. In the case of high energy research,

consideration must be given to periodic sequences of such fission pulses, between which the atomic RL is cooled, by some means or other of organized heat outflow. Apparently, the intervals of time in this case may comprise $\tau_0 \sim 10^{-4} \div 1$ sec. We shall confine ourselves to examining only the order of magnitude of atomic-reactor and optical parameters of the simplest self-modulation system of a thermally pulsed RL with rapid neutrons. Disregarding the role in this equipment of delayed neutrons and not taking into account the three-dimensional nonuniformities of the problem (and consequently the characteristic time of neutron redistribution over the active volume), we may write the following equation for the energy intensity of such a RL

$$\frac{dW}{dt}(t) = \frac{\rho(t)}{\tau} W(t), \tag{20}$$

where $\rho(t) = (k-1)/k$ is the equipment reactivity; k — the breeding ratio of neutrons in one "generation"; τ — average lifetime of neutrons in the given reactor. In the self-modulation RL system being discussed, the pulse of nuclear fissions is formed by rapid transfer of the system from a subcritical state in terms of neutrons to a supercritical state, i.e., the function $\rho(t)$ at the moment it is switched on $t = 0$ changes sign: /119

$$\rho(t) < 0 \quad \text{for} \quad t < 0; \quad \rho(0) = \rho_0, \quad \rho_0 > 0.$$

After this, the reactivity decreases with a temperature increase T of the gas-phase active medium filling the RL. The fission intensity increases more slowly, then decreases and the reactor ceases to operate.

Just as in the steady state problem, we shall use the concept of the critical temperature T_{kp}. When this is exceeded the efficiency drops of the light liberation of fission energy from the RL. Let us assume that $W_{кр}^{имп}$ is the critical energy intensity corresponding to this medium temperature. We shall show that under the conditions of a thermally pulsed RL mode, this value may exceed by several factors the value of $W_{кр} = W_{кр}^{ст}$ derived above for steady state conditions of the RL. We shall use q to designate the portion of liberated

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(starting at the switch-on moment t = 0) energy of nuclear reactions, and we may write in the general case

$$\frac{dT}{dt}(t)+\frac{1}{\tau_{охл}}[T(t)-T_0]=\frac{q}{N}W(t);\quad T_0=T(0), \tag{21}$$

where $\tau_{охл}$ is the characteristic cooling time of the gas-phase medium; T_0 — constant wall temperature. In the steady state mode, when $W(t)\equiv W_0$ at $t>0$, we obtain

$$T(t)=T_0+\frac{q}{N}W_0\tau_{охл}\left[1-\exp\left(-\frac{t}{\tau_{охл}}\right)\right].$$

The quantity $W_{кр}^{ст}$ is determined under the conditions of a constant temperature $T(\infty)=T_{кр}$ so that

$$W_{кр}^{ст}=\frac{N}{q\tau_{охл}}(T_{кр}-T_0). \tag{22}$$

In the problem of the pulsed RL, in which we are now interested, changes in ρ(t) and W (t) form the operational mode. Therefore, in very general conditions it is necessary to solve the differential equations (20) and (21) concurrently, using the connection between reactivity and temperature. We still cannot specify the contribution (which depends on the selection of the RL construction) of different mechanisms to the reactivity decrease determined by the temperature increase. Under the reactor-laser conditions, this is primarily determined by a decrease [with an increase in T = T (t)] of both the effective density of the gas-phase fissionable material, and the interaction cross section of the U^{235} nucleus with neutrons. We shall confine ourselves to the case of a linear dependence:

$\rho(t)=\rho_0-\gamma[T(t)-T_0]$. We shall assume that the characteristic cooling time of the medium is very high or, more precisely, $\tau_{охл}\gg\tau$. Then, according to Equation (21) the temperature increases in proportion to the energy of nuclear fission liberated in the medium:

$$T(t)\simeq T_0+\frac{q}{N}\int_0^t W(\xi)\,d\xi.$$

Under these conditions the relationship between the reactivity and changes in the energy intensity acquires the simple form

$$\rho(t) = \rho_0 - \Gamma \int_0^t W(\xi)\, d\xi, \qquad \Gamma = \frac{q}{N}\gamma,$$

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or, which is the same thing:

$$\frac{d\rho}{dt}(t) = -\Gamma W(t), \qquad \rho(0) = \rho_0. \tag{23}$$

The solution of a nonlinear system of two differential equations of the first order (20), (23) with the initial conditions $\rho(0) = \rho_0$, $W(0) = W_0$ may be represented in the form

$$W(t) = 4W_m \exp\left(\frac{t_m - t}{\tau_0}\right)\left[1 + \exp\left(\frac{t_m - t}{\tau_0}\right)\right]^{-2}. \tag{24}$$

Thus, as may be readily seen $W_m = \rho_0/2\Gamma\tau$ is the peak energy intensity; t_m — moment at which it is achieved; the quantity $\tau_0 = \tau/\rho_0$ has the meaning of the total (in the model of a pulsed RL) time of relaxation of the atomic-reactor system. According to expressions (20), (23) which we presented earlier, the nature of the pulse (24) is formed due to the fact that, beginning at the moment the reactor is switched on t = 0, the reactivity monotonically decreases, slowing down the increase (at $\rho > 0$) of the energy intensity. At the moment $t = t_m$ the reactivity decreases and passes through zero, after which the quantity W(t) also decreases. Thus, by temperature self-modulation of the reactivity, a pulse of the nuclear fission is formed in the RL system being discussed. As a rule, the pulse of light is somewhat shorter.

Figure 6 shows the dependence on time of the atomic - reactor characteristics in a self-modulation system. The characteristic cooling time of free electrons of the plasma filling the pulse RL is very low. It amounts to nanoseconds, and in the majority of cases is not taken into account for a molecular gas density of $N \gtrsim 10^{20}$ $см^{-3}$ in which we are interested. The relationship between the time τ_{N_e} of plasma recombination and the time τ_0 of atomic-reactor relaxation may differ. We shall first assume that $\tau_{N_e} \ll \tau_0$. Then the beginning $t_{(1)}$ of laser generation coincides with the moment the energy intensity of the reactor achieves the threshold value of $W(t_{(1)}) = W_{пор}$. Thus, the condition $W_m > W_{пор}$ must be satisfied for the generation

to occur. At $\tau_{N_e}'' \gg \tau_0$ the reactor should be constructed so that at the time t_m at which the maximum energy intensity is achieved in it, the temperature does not exceed the critical value T_{kp}. The moment $t_{(2)}$ that laser generation stops is determined under these conditions by the smaller of two limiting values $t_{(2)} = \min(t_{(2)}', t_{(2)}'')$; $T(t_{(2)}') = T_{кр}$ $W(t_2'') = W_{пор}$. According to Formula (5.5) the moment of the energy intensity maximum and the moment that laser generation begins differ from the relaxation time τ_0 by the logarithmic factors

$$t_m \simeq \tau_0 \ln\left(4\frac{W_m}{W_0}\right), \quad t_{(1)} \simeq \tau_0 \ln\left(\frac{W_{пор}}{W_0}\right).$$

In order to use the fission energy efficiently, the parameters of the device must be selected so that the relationship $t_{(2)} \gtrsim t_m$ is satisfied. The effectiveness of removing the energy from the reactor by means of a laser is reflected in the value of q. Naturally, this depends on the temperature T. In the calculations we can disregard the dependence of q on T, which is most strongly apparent before the critical temperature is achieved. At $t_{(2)} \lesssim t_m$ in this case we have /121

$$\left[1+\exp\left(\frac{t_m - t_{(2)}}{\tau_0}\right)\right]^{-1} = \left[1+\exp\left(\frac{t_m}{\tau_0}\right)\right]^{-1} + \frac{(T_{кр}-T_0)N}{4W_m q\tau_0}.$$

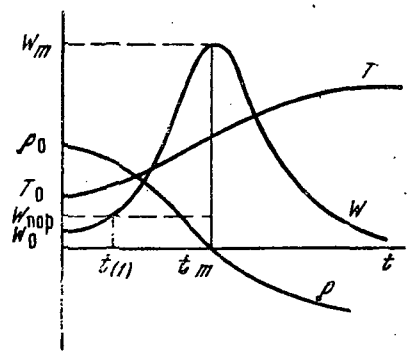

Figure 6.

It thus follows that the peak power of the light is maximum at $t_{(2)} = t_m$, and the duration of laser emission pulses may be determined by the quantity

$$\Delta' = t_m - t_{(1)} \simeq \tau_0 \ln\left(4\frac{W_m}{W_{пор}}\right)$$

If we have $W_m \gg W_0$, then

$$(W_m)_{max} \simeq \frac{N(T_{кр}-T_0)}{2q\tau_0}, \qquad (25)$$

which is related to the simple relationship between the parameters of the pulsed RL beam analyzed

$$\rho_0 = \gamma(T_{кр} - T). \qquad (26)$$

Assuming $W_{кр}^{имп} = (W_m)_{max}$, from (22), (26) we obtain

$$W_{кр}^{имп} \simeq \frac{\tau_{охл}}{2\tau_0} W_{кр}^{ст}. \qquad (27)$$

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We should recall that in the system of a steady state RL discussed above, the energy liberating elements (EDEL) have the form of long tubes with a small radius R, and the heat is removed by thermal conductivity from the medium to the wall. In the case of ordinary molecular thermal conductivity, the characteristic cooling time of the gas $\tau_{охл} \simeq \sigma_{упр}/R^2N/(4v_T)$, assuming that the cross section of elastic collisions equals $\sigma_{упр} \approx 10^{-15}\ см^2$ and setting the thermal velocity at $v_T \approx 10^5\ см \cdot \sec^{-1}$ when $R \approx 1\ см$, $N \simeq 3 \cdot 10^{20}\ см^{-3}$. We thus obtain $\tau_{охл} \simeq 1$ sec. In the case of natural or forced convection in EDEL, such a characteristic time may be decreased by two-three orders of magnitude. The reactor relaxation time essentially depends on the initial reactivity. It is thus necessary to use the values $\rho_0 \approx 10^{-2} \div 10^{-1}$. At $\tau \simeq 5 \cdot 10^{-6}$ we then obtain $\tau_0 \approx 5 \cdot 10^{-5} \div 5 \cdot 10^{-4}$ sec. Thus according to (28) the critical power of a pulsed reactor may exceed by 3-4 orders of magnitude the value calculated for a steady state RL mode without convection.

If we are not considering achieving the maximum emission intensity in a pulsed mode, but rather obtain optimum conversion of fission energy into light, we must change to the RL parameters for which $T(t_{(2)}) \simeq T_{кр}$. Thus

$$t_{(2)} \simeq \tau_0 \ln [(16W_m^2)/W_0W_{пор}],$$

so that, as compared with the previous calculation, the duration of the emission pulse doubles

$\Delta'' \simeq t_{(2)} - t_{(1)} \simeq 2\tau_0 \ln (4W_m/W_{пор}) \approx 2\Delta'$. The critical energy intensity of the reactor in this mode decreases as compared with $W_{кр}^{имп}$:

$$W_{кр}'' \approx \frac{N(T_{кр} - T_0)}{4q\tau_0} - \frac{W_{пор}}{4} \approx \frac{1}{2}\left(W_{кр}^{имп} - \frac{W_{пор}}{2}\right).$$

It now seems to us that it is more unlikely, but still possible, to realize another limiting state of the characteristic RL times $\tau_{N_e} \gg \tau_0$. Under such conditions the value of the maximum energy intensity of the reactor does not play a role in the process (in which we are interested) of extracting its energy by means of light. All of the light characteristics are only determined by the total fission energy per pulse $E^{имп} \simeq \int_0^\infty W(t)\,dt$. In analyzing the limiting relationship

of the operational conditions of a pulsed RL connected with this, there is no sense in resorting to the self-modulation system or using formula (24) for the change in energy intensity with time. The parameters of such an RL must be selected based on the fact that the medium cannot be overheated above a temperature T_{kp} which is critical for the laser problem. Thus, it is necessary to perform the calculations only for the heat capacity C of the gas, without taking into account its thermal conductivity during a pulse; $C(T_{кр} - T_0) = E_{max}^{имп}$. Under these conditions, we must examine the possibility of using not only thermally but also optically pulsed modes of RL operation — modulation of the quality of an optical resonator (possibly, the method of mode synchronization). Using an RL, this type of solution makes it possible to produce light pulses of very high energy and duration $\tau_{спст} \sim 10^{-9} \div 10^{-8}$ sec. / 122

The calculation results indicate that, in the simplest self-modulation system of a thermally pulsed RL, generation parameters will be achieved which are very high as compared not only with existing parameters, but also with those predicted by laser systems. In pulsed RL systems, it is possible to use even photodissociative transitions of separated molecules (such active media, as is known, are rapidly overheated). An appreciable reserve is now apparent for future overloading of the pulsed RL mode. It consists of the transition to two-cascade self-modulation systems, and also systems of the sub-critical type. In the latter, the reactivity remains negative, and the atomic-reactor device transfers the flux of neutrons (which is external to it) formed by the relativistic electron beam (in this case it is assumed that we are discussing "booster" systems) from the pulsed thermonuclear device (thus we are speaking of "hybrid" systems). In this connection, it is advantageous to note the important possibilities of using pulsed RL systems to create a pulsed thermonuclear device and to thus obtain a single energy-producing device which operates in a mode of periodic pulses. In the latter, a pulse of thermonuclear neutrons with high energy is passed through the subcritical atomic RL, formed in this case without enrichment of uranium with the isotope U^{235}. The light pulse produced as a result of the fission of uranium is directed partially toward producing the subsequent thermonuclear pulse.

FURTHER DEVELOPMENT OF THE PROBLEM

It appears to us that we have outlined the preliminary directions to be pursued by work on correcting and implementing the basic RL ideas. The pressing nature of this work is now determined by the apparent necessity of mankind to find methods for efficiently utilizing energy, and for the possibilities of the systems proposed to solve this problem.

Based on the features of the systems discussed here, we shall itemize (without taking into consideration their sequence in terms of importance or of time), the basic measures to be followed in implementing such systems.

1. It is necessary to establish the laser activity of several variations of filling EDEL. The most efficient experimental method at present consists of analyzing the optical characteristics of the dense plasma produced in the persistence of the sharply cut off pulse of the transverse field. It would be desirable to start as fast as possible research on the properties of uranium hexafluoride in a mixture with fluorine, and also thalium fluoride with fluorine.

2. It is necessary to analyze the amplifying possibilities of dense gases of an appropriate composition ionized by an electron beam both in steady state and in pulsed conditions. It is necessary /123 to investigate the properties of media with a combination of laser-active and nuclear-active components, placing the vessel in a neutron field of the necessary strength (in an atomic reactor of the traditional type).

3. It is necessary to analyze the operation of the simplest gas-phase reactors of the type discussed here.

4. The search must be continued for media for filling EDEL which will amplify the emission under conditions of supercooling of electrons. In addition to laboratory analysis of the optical properties of UF_6 and TlF in mixtures with fluorine, it is necessary to perform chemical and thermodynamic studies of the

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conditions for prolonged maintenance of the chemical composition of the required gas mixtures.

5. Studies must be performed on a theoretical analysis and laboratory implementation of different modes of heat transfer from the gas filling the EDEL.

6. Attention must be paid to solving the chemical-engineering problems related to the prolonged coexistence of EDEL walls with a very active content. The question must be considered of maintaining an operational state the end mirrors and optical windows for withdrawing the high energy emission from the reactor.

7. It is necessary to study the problem of the design of EDEL. The competing systems may be those which are more traditional for lasers - straight tubes with end mirrors, the great number of which ($\sim 10^4$) provides the criticality - and the less traditional lasers - spiral tubes of great length.

8. Neutron-reactor research must be carried out on possible active media. Analyses must be made of the behavior of neutrons in long tubes, and the stability conditions for their uniform distribution in terms of length. The dependence of density of the gas phase fissionable material within EDEL must be examined. The propagation of a pulse of rapid neutrons in non-steady state RL systems must be studied. Rapidly switching on the reacticity under conditions of a pulse-phase reactor of high energy must be examined.

9. Training must be begun for physics faculties in the corresponding specialties. There is still no information on the non-traditional methods (which are necessary in the studies) for producing dense supercooled plasma. Also there has been no experience with a theoretical analysis of such media in the programs of universities and engineering-physics institutes.

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